論　文　の　内　容　の　要　旨

論文題目　「Earthquake–Tsunami Multihazard Analysis Considering Foundation Uplift of Structure」

（構造物基礎の浮き上がりを考慮した地震と津波の複合災害の解析）

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Chapter 1 Introduction: Structures in coastal areas might be damaged by a large-scale tsunami generated due to large intensive earthquakes, such as the 2004 Sumatra–Andaman Earthquake or the 2011 Great East Japan Earthquake. Therefore, there is an urgent need for an evaluation method that describes the effects of complex earthquake–tsunami disasters on structures. Although research on earthquake–tsunami multihazard has recently gained considerable attention, few studies have investigated soil–structure interaction, particularly nonlinear soil–structure interaction, such as foundation uplift. In the 2011 Great East Japan Earthquake, numerous buildings were overturned and washed away because of the complex disaster caused by the earthquake and subsequent tsunami. This phenomenon is directly linked to the tragic loss of human lives and must be prevented. Accordingly, this study aims to further develop the earthquake–tsunami interaction diagram introduced by Carey et al. (2019) by considering foundation uplift. This study is essential for assessing damage to humans caused by complex earthquake–tsunami disasters. The expected results will provide valuable information for the efficient reinforcement of buildings against not only earthquake disasters but also earthquake–tsunami multihazard scenarios in the future.

Chapter 2 Seismic Response of Linear Structure Systems Considering Foundation Uplift: Before generating earthquake–tsunami interaction diagrams considering foundation uplift, this study presents the basic phenomenon of foundation uplift in Chapter 2. This chapter presents two types of buildings, low- and medium-rise, on a shallow foundation sustained by three types of soil, namely, soft soil, stiff soil, and rock, as analytical models. Five recorded ground motions with different frequency characteristics are prepared to discuss the influence of frequency and intensity characteristics. Several numerical models can be used to calculate seismic responses considering foundation uplift, such as the macroelement model, which considers soil nonlinearity, or the horizontal–vertical interactive Sway–Rocking model, which considers geometrical nonlinearity owing to foundation uplift. Eventually, this chapter compares and discusses two representative models considering foundation uplift from the perspective of uplift behavior. The calculation results highlight the similarity in structural responses between the two numerical models for structures located on stiff soil and rock despite a notable disparity in the ground contact ratio for both models. Moreover, plastic deformation of the soil could mitigate foundation uplift. The comparison results also indicate that the degree of foundation uplift depends on the structure characteristics, seismic input motions, and soil conditions.

Chapter 3 Seismic Response of Nonlinear Structure Systems Considering Foundation Uplift: For a deeper understanding of the foundation uplift phenomenon, Chapter 3 discusses effects of foundation uplift on structures from the perspective of structural responses and energy. The structures are based on the linear assumption described in Chapter 2. However, Chapter 3 examines the seismic response considering structural nonlinearity and foundation uplift. Furthermore, for an explicit discussion of the effect of foundation uplift, Chapter 3 introduces three scenarios: the fixed-base case (i.e., soil–structure interaction is not considered), the structure that considers soil–structure interaction without considering foundation uplift (linear SSI), and the structure that considers foundation uplift (nonlinear SSI). The obtained results demonstrate that foundation uplift positively affects the structure. It interrupts seismic motion, thereby reducing structural acceleration responses. Furthermore, foundation uplift may reduce the formation of a hysteretic loop or the accumulation of nonlinear deformation in the superstructure, resulting in less irrecoverable hysteretic energy. However, in cases where the structure experiences high-intensity and low-frequency ground motion, foundation uplift may adversely affect structural responses. Excessive foundation uplift under such conditions can render the structure unstable, a situation that must be diligently avoided.

Chapter 4 Earthquake–Tsunami Multihazard Analysis Considering Foundation Uplift: After understanding the physics of foundation uplift problems through the discussion presented in Chapters 2 and 3, Chapter 4 studies the earthquake–tsunami disaster with consideration of foundation uplift problems. Damage position cannot be estimated precisely, and building or foundation damage has a dominant effect that would differ depending on the seismic motion characteristics. Therefore, this study develops Carey's (2019) earthquake–tsunami interaction diagram by considering foundation uplift and concurrently determining two different limit states—interlayer deformation angle and foundation uplift—to evaluate the impact of sequential earthquake–tsunami hazards. Using a three-story building supported by a mat foundation on stiff soil as a model, the 30 ground motions recorded in the coastal areas of three prefectures in the Tohoku region during the 2011 Tohoku earthquake were applied. In addition, the tsunami hydrodynamic force was considered and its magnitude was varied to generate an earthquake–tsunami interaction diagram. The diagrams particularly demonstrate that residual effects of earthquake loading reduce the structure's resistance to subsequent tsunami loading. The findings indicate that the dominant damage depends on the input seismic characteristics because damage can differ for each case. Therefore, multiple consider limit state is necessary for complex disaster prevention.

Chapter 5 Conclusions: Chapter 5 summarizes the results obtained in Chapters 2–4. This further developed an existing earthquake–tsunami interaction diagram to consider nonlinear soil–structure interaction with foundation uplift, which remarkably affects the behavior of structures, including structural responses and nonlinear behavior. Before developing the diagrams, this study investigated the effect of foundation uplift on structural responses. This research will offer valuable insights into the efficient reinforcement of buildings against not only earthquake disasters but also earthquake–tsunami multihazard scenarios in the future.